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Reading development and dyslexia in a transparent orthography: a survey of Spanish children

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Abstract Spanish-speaking children learn to read words printed in a relatively transparent orthography. Variation in orthographic transparency may shape the architecture of the reading system and also the manifestation of reading difficulties. We tested normally developing children and children diagnosed with reading difficulties. Reading accuracy was high across experimental conditions. However, dyslexic children read more slowly than chronological age (CA)-matched controls, although, importantly, their reading times did not differ from those for ability-matched controls. Reading times were significantly affected by frequency, orthographic neighbourhood size and word length. We also found a number of significant interaction effects. The effect of length was significantly modulated by reading ability, frequency and neighbourhood. Our findings suggest that the reading development of dyslexic children in Spanish is delayed rather than deviant. From an early age, the salient characteristic of reading development is reading speed, and the latter is influenced by specific knowledge about words.

Keywords Spanish · Reading · Development · Dyslexia · Frequency · Length · Neighbourhood

Introduction

We can attribute greater or lesser transparency (or depth) to different orthographies according to how they vary both in the consistency of mappings between orthography and

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phonology and in the complexity of syllabic structures (Seymour, Aro, & Erskine, 2003; see also Frost, Katz, & Bentin, 1987; Katz & Feldman, 1981). In languages like Spanish and Italian, two more transparent orthographies, mappings between graphemes and phonemes are consistent across word types. This contrasts with languages like English, a more opaque orthography, in which there is inconsistency across a substantial number of words in the pronunciation of similar spellings (Ziegler, Stone, & Jacobs, 1997). In relation to syllabic complexity, Seymour et al. (2003) contrast Romance languages, such as Italian or Spanish, in which most syllables have 'open' consonant–vowel forms, with Germanic languages, such as English or German, in which there are many 'closed' consonant–vowel–consonant syllables and complex consonant clusters in both onset and coda positions. It is readily supposed that these variations could give rise to differences in how reading develops and, thence, in how reading difficulties are manifest (Frost et al., 1987; Seymour et al., 2003; Ziegler & Goswami, 2005).

The findings of a large-scale cross-linguistic survey of learning to read, reported by Seymour et al. (2003), indeed indicated that English children take longer to reach basic competence in reading words and nonwords (letter strings created by the experimenter) than children reading in languages with relatively more transparent orthographies, for example, Italian, Spanish or German. Similar contrasts are apparent in a number of other cross-linguistic studies (Bruck, Genesee, & Caravolas, 1997; Ellis & Hooper, 2001; Frith, Wimmer, & Landerl, 1998; Goswami, Gombert, & de Barrera, 1998; Wimmer & Goswami, 1994), as well as in the comparison of observations yielded by monolingual studies (Cossu, Gugliotta, & Marshall, 1990; Porpodas, Pantelis, & Hantziou, 1990, Sprenger-Charolles, Siegel, & Bonnet, 1998). The question that surely follows asks: Could the differences in the challenges to learning presented by variation in orthographic transparency cause the architecture of the reading system to develop in qualitatively different ways? Theoretical approaches to this question may take three distinct forms.

One approach, proposed by Ziegler and Goswami (2005), maintains that, everything being equal, a child learning to read a deep orthography, in which inconsistent orthography-to-phonology mappings are encountered, will develop different kinds of representations compared to a child learning to read a more shallow or transparent orthography. Thus, a child learning to read in English is impelled to acquire orthography-to-phonology mappings at varying grain sizes to cope with the presence of irregularly or inconsistently pronounced spellings. Grain size is the level of detail of the mapping or the size of a unit orthography-to-phonology mapping (the number of letters collected under the unit mapping). Here, grain sizes may vary from the grapheme–phoneme level to the rime level to the lexical level. Graphemes are the single letters or double letters that correspond to phonemes, that is, to significant sounds in a language. Words of one syllable can be broken up into the onset, the initial sequence of consonants, and the rime, everything that follows. For example, "street" can be divided into onset "str_" and rime "_eet". Lexical mappings are mappings between the representations of the complete letter string spelling a word and the complete phonology of its pronunciation. A multiple grain size strategy, in this view, helps to support in English both reading aloud and the phonological recoding that serves developmental word recognition. In contrast, a child learning to read a more transparent language, for example, Italian or Spanish, may rely on grapheme–phoneme mappings alone, as the occurrence of irregular words is rare (see, for a proposal with broad similarities, Seymour et al., 2003.)

A second approach is embodied by the Orthographic Depth Hypothesis (Frost et al., 1987; Katz & Feldman, 1981) in which it is presumed that both lexical and sub-lexical mappings are available for orthography-to-phonology coding and for word recognition, but it is hypothesized that the relative weighting of each strategy is driven by the relative transparency or depth of the orthography being read. The assumption of lexical and sub-lexical strategies for reading is the principle building block of the dual route account of reading (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). By this assumption, one supposes that words can be read aloud via direct lexical orthography-to-phonology mappings (dependent upon knowledge about how the whole word is pronounced from its spelling) or through the assembly of the products of sub-lexical mappings, here, grapheme-phoneme correspondences (dependent upon knowledge about how graphemes, the sub-lexical units, are usually pronounced). A more transparent orthography permits greater reliance on sub-lexical mappings because such mappings reliably deliver correct pronunciations. A less transparent orthography would be read with relatively greater reliance on lexical mappings because the assembly of sub-lexical mappings would frequently yield incorrect pronunciations: An irregularly pronounced word like "pint" would require the exceptional, word-specific, pronunciation of "i" that could be stored in one's lexicon rather than the usual pronunciation that the sub-lexical mapping, the grapheme-phoneme correspondence, would deliver.

Essentially, the strong versions of the psycholinguistic grain size and the orthographic depth views presume a reliance on grapheme–phoneme correspondences in reading in transparent orthographies. It may be that such views can be tempered by allowing that a reliance on sub-lexical mappings characterises reading early in development but that, as the reader matures, larger grain size mappings are established to serve more rapid phonological coding. However, we submit that a third possibility must be entertained, that larger grain size mappings are acquired by children quite early in development (as we discuss below, this is a possibility empirically motivated and discussed, in particular, by investigators of reading in Italian). This is because the frequent occurrence of words between two and four syllables in length is an aspect of transparent orthographies like Spanish or Italian that would exert substantial time penalties given a grapheme-by-grapheme phonological coding strategy. Such time penalties could motivate the development of larger grain size mappings enabling the pronunciation of larger collections of graphemes at a time, for example, lexical mappings, even in languages where accurate phonological coding is attainable through the grapheme–phoneme mappings alone and even where such sub-lexical mappings can be practised to asymptotic efficiency. In this view, the influence of lexical knowledge might be evidenced early in development by the facilitation of reading speed.

This is not to deny that the evidence is striking that children reading in less transparent orthographies are more affected by larger grain size analogies, for example, as indicated by the greater advantage garnered by English compared to German children in reading words with more rime body neighbours, where body neighours are words that share the same rime or body, for example, "street, meet, feet" (Ziegler, Perry, Ma-Wyatt, Ladner, & Schulte-Körne, 2003; see, also, findings concerning the exploitation of rime or lexical analogies in nonword reading reported by Goswami, Porpodas & Wheelwright, 1997; Goswami et al., 1998; Goswami, Ziegler, Dalton, & Schneider, 2001). However, studies conducted in Italian have yielded strong evidence that phonological coding of print in transparent orthographies can be influenced by lexical or morphological properties from quite early in development. Thus, Burani, Marcolini and Stella (2002) have shown that children reading nonwords are faster and more accurate when those nonwords include morpheme constituents. Further, Burani et al. (2002; see, also, Barca, Burani, Di Filippo, & Zoccolotti, 2007) report that, in the same study, children were faster to read higher frequency words. The advantage putatively lent by knowledge of larger grain size mappings, whether involving morphological or lexical units, can be understood as arising from the savings gained by using preassembled units for orthography-to-phonology coding. Such an advantage might be hypothesised to be available, equally, to Spanish readers.

If there are differences in development relating to orthographic transparency, are there differences, also, in how specific reading difficulties are manifested? It is commonly assumed that the behaviours seen in dyslexic adults and children stem from problems of phonological processing (Ramus et al., 2003; Snowling, 2000; Vellutino et al., 2004). Phonological recoding of print is an important component of learning to read (Jorm & Share, 1983, Jorm, Share, McLean, & Matthews, 1984) so that a phonological impairment would make it harder for a developing reader to map the orthography of newly confronted letter strings to the phonology of known words.

In an influential discussion of the symptoms of reading difficulties in transparent orthographies, Wimmer (1993) argued that, in such orthographies, phonological impairment could impact demonstrably on reading speed but less markedly, if at all, on accuracy. A reading speed deficit could stem from multiple locations, however. It is acknowledged by Wimmer (1993, after Frith, 1985, and Coltheart, 1978) that children may develop adequate grapheme-to-phoneme mappings but fail to establish lexical orthographic input representations, that is, representations corresponding to knowledge about the spellings of words that function as keys for access to other knowledge about the words. Such a 'surface dyslexic' impairment would be evidenced in slow, serial, reading but would be associated with an impairment of orthographic input. Relatedly, it is also possible that slowed reading may be manifest in a transparent orthography not as the result of a failure to acquire lexical orthographic representations but as the result of a failure to develop a more parallel, less serial, mode of grapheme-to-phoneme coding. Further, a reading speed deficit could arise from a failure to automatise reading processes (see, e.g. Nicholson & Fawcett, 1990).

The association of variation in the phenomena of reading difficulties with variation in orthographic transparency can be most clearly seen in cross-linguistic comparisons exemplified by recent studies in which the reading of German and English children have been compared using stringently matched stimuli (Landerl, Wimmer, & Frith, 1997; Ziegler et al., 2003). Landerl et al. (1997) showed that, although German dyslexic children were much more accurate than English dyslexic children in reading words and non-words, the German dyslexic children were significantly less accurate (14% of responses were errors) than the same-language reading-ability-matched controls (10% errors). Nevertheless, Wimmer (1993) reported that, whereas German dyslexic children made few errors in word and nonword reading, they did evidence dramatic reading speed deficits (see, also, Wimmer, 1996a, 1996b). Likewise, Ziegler et al. (2003) found that, whereas German children were faster and more accurate than English children, in both languages dyslexic children were no less accurate but were significantly slower than the reading-ability-matched controls. Such observations argue that the critical aspect of dyslexia in transparent orthographies is slowed reading speed (see, also, De Jong, 2003; De Jong & van der Leij, 2003).

In the present study, our aim was to specify the nature of the strategies used by children learning to read in Spanish and to specify the nature of the reading difficulties evidenced by dyslexic children. We measured both reading accuracy and reading times, as it was expected that reading accuracy would be high overall but that younger or less skilled readers would read more slowly. To elucidate the characteristics of the reading process, we presented words that varied in length, frequency and orthographic neighbourhood size.

It is commonly observed that longer words are read more slowly, sometimes also less accurately, than shorter words. This finding has been reported in a number of languages of varying orthography transparency (e.g. Barca, Burani, & Arduino, 2002; Juphard, Carbonnel, & Valdois, 2004; Spinelli, De Luca, Di Filippo, Mancini, Martelli, & Zoccolotti, 2005; Weekes, 1997; Ziegler et al., 2003; Zoccolotti, De Luca, Di Pace, Gasperini, Judica, & Spinelli, 2005), including Spanish (Cuetos & Barbón, 2006, Jiménez & Hernández, 2000). Moreover, while the effect has been demonstrated in adults and children, it has been shown that the length effect is larger for younger or less-skilled developing readers (Burani et al., 2002; Spinelli et al., 2005; Ziegler et al., 2003; Zoccolotti et al., 2005). Accounts of the length effect begin with the observations that there are greater length effects in reading low-frequency words (there may be no length effect for high-frequency words) and that, whereas the length effect for low frequency words may be confounded with variation in neighbourhood size, the length effect for nonwords appears to have independent significance (Weekes, 1997). These data have led to the view that the length effect reflects the operation of a serial, that is, grapheme-by-grapheme, sub-lexical phonological coding process. Such a process is assumed to be used for nonword reading in the dual route account (Coltheart et al., 2001; Weekes, 1997), but it may also be operational, in accounts assuming single routes for reading (Ans, Carbonnel, & Valdois, 1998; Plaut, 1999), where inexperience or impairment of orthographic coding or of visual attention restrict the function of parallel or global letter string processing in word reading.

Higher frequency words are read more quickly and accurately than less frequent words (e.g. Balota & Chumbley, 1985; Monsell, 1991). However, whereas the effect of frequency has been reported to influence reading in Italian adults and children (Barca et al., 2002; Barca et al., 2007; Burani et al., 2002), Cuetos and Barbón (2006) report that Spanish adult reading latencies are affected by lexical age-of-acquisition not by frequency. Again, it has been found that frequency effects appear to be greater for younger or less able readers (Barca et al., 2007).

The observation of a frequency effect in children's reading has been argued (Barca et al., 2007; Burani et al., 2002) to reflect the operation of lexical mappings in developmental reading (within a dual route framework), but it must be acknowledged that the effect of frequency is readily explained in accounts of reading (e.g. Seidenberg & McClelland, 1989) which assume that, as a result of experience, connection weights between the units of distributed representations gradually change to reduce error. In connectionist models like the Seidenberg & McClelland (1989) model, phenomena such as the frequency effect on reading can be simulated quite well even though it is not assumed that lexical knowledge is tied to unitary representations consisting of word-specific nodes. In such models, it is assumed that the representation of knowledge is distributed—many representational units are involved in storing knowledge about each word, and each unit is involved in storing knowledge about more than word—and, secondly, that learning takes place through the gradual adaptation of connections between these units so that the system can optimise responses in correspondence to experience. These assumptions are sufficient for frequency effects to result simply because frequent experiences wring greater adaptations in the connections between representational units. Consequently, it may be more conservative to suppose that frequency effects reflect experience of orthography-to-phonology mappings and that, while such experience may underlie lexical knowledge, it need not be assumed to reflect the influence of the properties of unitary lexical representations.

The effect of orthographic neighbourhood size on reading has been the controversial subject of a substantial body of research. Orthographic neighbourhood size is calculated as the number of words that can be produced by replacing a single letter of a word or nonword (Coltheart, Davelaar, Jonasson, & Besner, 1977). While there appears to be little consistency in relation to the significance or direction of the neighbourhood size effect in word recognition tasks such as lexical decision (e.g. Andrews, 1989, 1992; Coltheart et al., 1977; Grainger, 1990; Grainger, O'Regan, Jacobs, & Segui, 1989; Laxon, Coltheart, &

Keating, 1988), it is commonly reported that words with many orthographic neighbours are read more quickly or accurately than words with fewer neighbours by adults (Andrews, 1989, 1992; Grainger, 1990) as well as by children (Laxon et al., 1988; see, also, Ziegler et al., 2003). The facilitatory neighbourhood effect has been observed for low but not high frequency words (Andrews, 1989, 1992), and neighbourhood size effects have been found to be greater for younger or less able readers (Laxon et al., 1988; Ziegler et al., 2003). Significantly, Ziegler et al. (2003) reported that English but not German children were found to present reduced length effects in reading words with many neighbours. The neighbourhood size effect has been taken to reflect the influence of larger, body or lexical, grain-size mappings. Reading can be facilitated, in this view, as a result of activation spreading from neighbouring lexical representations, activated in parallel by letter string presentation, to prime letter representations (Andrews, 1989) or to phonological representations (Coltheart et al., 2001). However, in the connectionist framework, a facilitatory neighbourhood size effect arises naturally because the reading of any one word is served by connections strengthened through the experience of reading its neighbours (Seidenberg & McClelland, 1989).

The present study extends the investigation of reading by testing the effects of length, orthographic neighbourhood size and frequency on the reading of Spanish-speakers, dyslexic children and children of age-average ability. We tested both chronological-age-matched and reading-ability-matched controls, as it is argued by Bryant and Goswami (1986; see, also, Backman, Mamen & Ferguson, 1984) that observed differences in comparisons between the control group children and children with reading difficulties may be ambiguous. A significant difference in a comparison with age-matched children could be confounded with the greater reading experience of the controls, and a null difference in a comparison with ability-matched children could be confounded with the higher mental age of the children with reading difficulties, who will tend to be older. Thus, research comparing groups of readers differing in ability most usefully affords both an age-matched and an ability-matched comparison.

Following previous researchers (Wimmer (1993; Wimmer & Goswami, 1994), we used a word list reading test procedure in which words were presented in sequence on a page. This was done to mimic natural reading. Perhaps more significantly, it was also done because, as the fundamental problem in dyslexia in transparent orthographies may subsist in the efficiency or speed with which individuals can read, it is important to record reading in terms that reflect both the duration of responses and the duration of the intervals taken between responses. In this respect, employing a reading list procedure rather than a discrete reading trials procedure allows us to test the automaticity of reading skills in a manner similar to that claimed for tests of rapid automatic naming (Denckla & Rudel, 1976).

Statement of research questions

In sum, we sought to elucidate the influences on reading in the developing reader in a language with a highly transparent orthography, Spanish. Our design focused on the influences of frequency, length and orthographic neighbourhood size. Based on previous research, we expected to find that words would be read more quickly and more accurately if they were shorter, more frequent words with larger neighbourhoods. We sought, additionally, to examine how dyslexia is manifested in Spanish. Research in other transparent orthographies, such as German, led us to expect that dyslexia should more likely be evidenced in slower reading speed than in decreased reading accuracy, although we presumed that, nevertheless, the dyslexic children would make more errors than the children in the control group. Of primary interest was the question of how relative reading ability (RA) would interact with the influence of psycholinguistic variables to determine reading performance. The impact of the psycholinguistic deficit hypothesised to underly dyslexia in most accounts was expected to entail a greater length effect in dyslexic reading because an impaired phonological processing capacity, wherever the impairment may lie, would be expected to accumulate delays in, for example, the phonological encoding of graphemes or grapheme strings, as well as the transitions between the encoding units after completion of each unit. We were not certain how reading ability would interact with the effects of frequency and neighbourhood. We have indicated how frequency and neighbourhood effects on reading have been argued in previous research to demonstrate the influence of lexical knowledge on reading. Dyslexic children could attempt to compensate for inefficiencies at the level of grapheme–phoneme coding by permitting greater influence on the process of phonological coding because of knowledge about how neighbours are coded, for instance. However, such influence may not obtain where reading difficulties have restricted the acquisition of vocabulary or the accumulation of reading experience. Thus, the question of how reading ability interacts with frequency or neighbourhood effects was for us, at the outset of our investigation, an open question.

Method

Participants

The participants were recruited from schools located in the provinces of A Coruña, Lugo, Orense and Pontevedra in northern Spain. An initial approach to teachers in schools yielded a sample of 110 individuals of varying age and RA. All participants were of lower–middle socio-economic status. No children were admitted to the sample who had been found to have poor attendance records or who had been diagnosed with deficits of neurological function or of sensory-motor ability. All 110 children were given a range of standardised and experimental RA and intelligence tests over a number of different school days through a 3-month period. The experimental data reported in the present article were gathered in a single session devoted to the experimental test alone, and the standardised reading test we discuss in this section was administered in a separate session.

From the initial sampling of 110, we selected children with clear reading difficulties (the DYS or dyslexic group), as well as a control group of children of clearly age-average or better reading ability. From the latter, we further selected control participants matched to the dyslexic participants on reading ability (the RA-matched group) or chronological age (the CA-matched group).

Selection of children for the different groups was based on performance in the word reading test in the PROLEC-R battery of tests of literacy skills (PROLEC-R, Cuetos, Rodriguez, Ruano & Arribas, 1996). All 110 children in the initial sampling were given the PROLEC-R word reading test. The test is administered individually and requires the child to read a list of 40 words aloud as quickly and as accurately as they can. These words vary quite broadly in frequency (items were high or low in frequency according to the Martínez & García (2004) analysis of primary school texts) as well as in length (items were between five and eight letters in length). Children's scores consist of an accuracy score and a reading speed, measured as the time taken to complete the task. The standardization sample for PROLEC-R consisted of a total of 920 children, of approximately equal numbers of boys and girls, tested across a number of different regions in Spain; about 150 children were tested in each primary school year (there are six primary school years). The reading test has been found to have internal consistency of Cronbach's alpha=0.74 (based on accuracy scores). The test is argued by its authors to be particularly informative if one computes a combined score, which we shall refer to as a measure of reading skill, equal to the accuracy divided by the reading speed then multiplied by 100. Reading skill on the word reading test was found to correlate with teacher ratings of RA for a sample of 408 children, $r=0.34$.

We selected to the dyslexic group those children whose reading accuracy was less than the mean−2 SD of the PROLEC-R standardization sample. We selected to the control group those children whose reading accuracy and also reading speed fell within the bounds set by the mean accuracy or speed±2 SD. We further selected from the control group children who were matched to the dyslexic group on CA, the CA group, and also younger children, the ability-matched RA group, who were matched to the dyslexic group on the combined reading skill measure. We report mean and standard deviations for PROLEC-R reading accuracy, reading speed and the combined reading skill scores for each group in Table 1. The DYS and RA groups did not significantly differ on reading skill ($t(42)=0.73$, $p=0.47$, two-tailed), but the DYS group obtained a lower reading skill score than the CA group ($t(42)=3.63$, $p=.001$, two-tailed). The DYS and CA groups did not significantly differ on age ($t(42)=-0.25$, $p=0.80$, two-tailed), but the DYS group was older than the RA group ($t(42)=2.77$, $p=0.008$).

All children in the initial sample of 110 were tested for general intelligence using the BADYG battery (Yuste, 2002). The BADYG consists of a set of six basic tests, the accuracy scores for which are summed to calculate a measure of general intelligence. The tests probe analogical reasoning, mental arithmetic, numerical reasoning, the ability to discern logical sequences (using an analogue of Raven's matrices), figure rotation and the ability to respond to complex instructions. An intelligence quotient is derived from the general intelligence score through a transformation that renders the mean equal to 100 and the standard deviation equal to 15. We report the mean and standard deviation of the intelligence quotient scores of the participant groups in Table 1.

A note on reading instruction in primary schools in Spain

The majority of primary schools in Spain teach reading with a focus on spelling–sound mappings corresponding to the syllable. Children are taught to pronounce consonants associated with vowels in simple consonant–vowel syllables, for example, "ma, me, mi,

Table 1 Summary of participant characteristics

Group	Chronological-age-matched mean (SD)	Dyslexic mean (SD)	Reading-ability-matched mean (SD)
Age (months)	121.1 (13.8)	122.2 (15.1)	111.3 (10.6)
PROLEC-R word reading accuracy (out of 40)	39.6 (.7)	36.4 (2.3)	39.5 (.7)
PROLEC-R word reading speed (s)	31.2 (5.9)	45.5 (15.9)	42.9 (12.2)
PROLEC-R reading skill (accuracy/speed)×100	131.9 (29.9)	92.4 (41.4)	100.8 (34.8)
BADYG intelligence quotient	82.0 (18.8)	71.5 (17.3)	84.9 (21.6)

mo, mu". Teaching builds on the pronunciation of these simple syllables by showing children how the syllables can be combined to construct words, for example, "mama". These lessons are then extended to wider sets of syllables by the association of different consonants with the same vowels, for example, "pa, pe, pi, po, pu". Further teaching extends to more complex syllables, for example, "cos" (a consonant–vowel–consonant syllable) and the construction of words from these latter.

Materials

We selected words to vary on lexical frequency, orthographic neighbourhood size and word length according to a factorial design (2×2×2, high or low frequency, many or few neighbours, short or long in length). The frequency estimates (frequencies of occurrence per million words) are taken from the LEXESP counts computed using a corpus of around 5 million words sampled from a wide variety of texts (Sebastián, Martí, Carreiras, & Cuetos, 2000). The orthographic neighbourhood size estimates are taken from the counts reported by Pérez, Alameda, & Cuetos (2003), based on the Diccionario de la Lengua Española (Real Academia de la Lengua, 1992). We created eight lists of 15 words each, constructing a different list for each condition, shown in Table 2.

Procedure

Each list was presented on an A4 sheet with the 15 words presented in five rows of three columns. Words were printed in the "Escolar" type-font (letters were 26 mm in height, on average) and viewed from a distance of about 30 cm. Students were tested individually during school hours. They were asked to read the words as quickly and as accurately as possible. We checked the students' understanding of the test instructions during a practice trial in which participants were asked to read aloud a list of 15 words varying in frequency, length and orthographic neighbourhood size within the range delimited by the critical items' characteristics.

To measure reading speed, we recorded reading times for entire lists, starting timing from the moment that a child was first shown the list and ending timing when the child had produced responses to all items on the list. No feedback was given during testing. Words that were incorrectly pronounced or incorrectly stressed were marked as errors. Self-corrections were marked as correct.

Table 2 Summary of frequency, neighbourhood and length of experimental list words

Condition	Frequency mean (SD)	Neighbourhood mean (SD)	Length (letters) mean (SD)
High frequency, many neighbours, short	98.7 (39.4)	12.5 (5.7)	5 (.9)
High frequency, many neighbours, long	148.9 (197.4)	4.0 (2.3)	8 (.9)
High frequency, few neighbours, short	172.4 (139.7)	1.1 (.7)	5 (.9)
High frequency, few neighbours, long	128.9 (92.7)	0.7 (.7)	8 (.9)
Low frequency, many neighbours, short	6.0 (7.1)	8.7 (2.3)	5 (.9)
Low frequency, many neighbours, long	8.7 (8.1)	4.5 (2.5)	8 (.9)
Low frequency, few neighbours, short	14.9 (16.1)	0.7 (.7)	5 (.9)
Low frequency, few neighours, long	6.9 (8.1)	0.9 (.9)	8 (.9)

Results

Data analysis

We analysed the accuracy of responses and reading speed (reading times) recorded for each child in relation to each word list. The use of a list reading method meant that our analyses of reading speed were by-subjects analyses done on the basis of reading times per list. In other words, no by-items analyses of reading speed were conducted. We used the generalised linear mixed-effects modelling (GLMM; Baayen, 2007) technique to analyse accuracy by examining what factors predicted the likelihood (really, the log odds) that a participant's response to an item would be correct. Where the data being analysed are dichotomous (1 correct, 0 incorrect), as here, assumptions essential to the validity of parametric statistics, such as homogeneity of variance or normality in the data distribution, do not obtain. The solution is to use logistic regression, as the latter can be considered the application of regression analysis to data transformed in such a way (to the log odds or logit of the accuracy per item) that one can test the importance of predictors of logit accuracy as components of a linear function (Howell, 2002) while avoiding the dangers inherent in conducting, for example, regression analysis of the proportions of items read correctly. Moreover, we used a mixed-effects modelling technique because GLMM allows us to examine accuracy at the level of raw scores (the accuracy of a response made by a subject to an item) and test what factors help us to account for variation in that accuracy including, simultaneously, the experimental factors of interest, frequency and so forth, as well as random variation because of differences between items or between participants sampled.

We report post hoc analyses of simple main effects and simple interaction effects where interaction effects were found to be significant in our analysis of reading times. We report only those analyses relating to questions of theoretical interest within the terms of our literature review to avoid inflating family-wise error rate unnecessarily (Howell, 2002). Simple effects analyses were conducted by analyzing only the data pertaining to the simple effect, with the error term derived from the same simple effect analysis (Howell, 2002). We report r as an index of effect size (Fields, 2007), where r was computed using the formula:

$$r = \sqrt{\frac{F(1,-)}{F(1,-) + df_{\text{error}}}}$$

for which $F(1,-)$ is the F ratio resulting from the relevant simple effect analysis.

Accuracy

The children tended to read at a high level of accuracy consistently across conditions in each group (see Table 3). However, the RA group made more errors than the CA children and the DYS children made more errors than the RA children. There is also a clear trend such that accuracy was greater to words of high frequency.

We tested the effects of group, frequency, neighbourhood size and word length in a GLMM analysis of reading accuracy in which we specified frequency, neighbourhood size, word length and participant group as experimental or fixed effects factors and subject and item as random effects factors. We tested for the effects of two-way interactions by specifying interaction terms carried by the multiplicative products of all possible pairings of the experimental factors: group × frequency, group × neighbourhood, group × length, frequency × neighbourhood, frequency × length, and neighbours × length. Before

Table 3 Summary of performance showing average word list reading times and error rate

Condition	Group		
	Chronological-age-matched	Dyslexic	Reading-ability-matched
High frequency, many neighbours, short			
mean speed in secs. (SD)	10.6 (2.5)	14.6 (4.5)	13.1 (3.9)
Errors (%)	2.1	3.6	1.5
High frequency, many neighbours, long			
mean speed in secs. (SD)	14.6 (3.7)	21.5 (8.0)	18.9 (5.1)
Errors (%)	1.5	4.8	2.4
High frequency, few neighbours, short			
mean speed in secs. (SD)	9.8 (3.0)	15.0 (8.9)	13.0 (3.9)
Errors (%)	0.3	3.3	2.1
High frequency, few neighbours, long			
mean speed in secs. (SD)	15.9 (4.9)	27.7 (18.0)	21.5 (7.5)
Errors (%)	0.9	8.8	3.9
Low frequency, many Neighbours, short			
mean speed in secs. (SD)	13.8 (3.7)	19.8 (5.8)	16.4 (4.2)
Errors (%)	2.1	7.6	4.2
Low frequency, many neighbours, long			
mean speed in secs. (SD)	18.0 (4.7)	26.5 (8.6)	21.8 (6.5)
Errors (%)	2.4	8.5	5.5
Low frequency, few neighbours, short			
mean speed in secs. (SD)	15.3 (5.4)	21.6 (7.7)	17.9 (5.4)
Errors (%)	4.2	9.4	6.4
Low frequency, few neighours, long			
mean speed in secs. (SD)	20.1 (5.9)	28.7 (9.3)	23.8 (6.0)
Errors (%)	1.8	10.0	3.3
Total errors	51	185	97

computation of the interaction terms, we standardised the psycholinguistic experimental variable values to militate against the risk of intercollinearity because of the correlation between the main effects and interaction term (multiplicative products) variables (Cohen & Cohen, 1983). We present the outcome of the analysis in Table 4. It can be seen that accuracy was significantly predicted by group and frequency. A model consisting of just the significant predictors was found to provide a good fit to the data: Somer's D_{xy}=0.70, where D_{xy} is the rank correlation between the predicted probabilities and the observed accuracy (see Baayen, 2007) and ranges between 0 (randomness) and 1 (perfect prediction). Note that we do not report R^2 because a simple correlation between observed accuracy and predicted probability of accuracy is not straightforwardly interpretable.

We coded errors as: word substitutions, for example, "nube" (cloud) → /nueve/ (nine); nonword errors, for example, "bigote" (moustache) → /bixote/; or stress errors, for example,

Table 4 Summary of generalized mixed-effects model of accuracy in reading

Parameter	estimate	SE
Fixed effects		
Intercept	−4.89***	0.30
Frequency	−1.26**	0.44
Neighbourhood	0.03	0.22
Length (letters)	0.01	0.19
Frequency × neighbourhood	−0.16	0.23
Frequency × length	0.15	0.16
Neighbourhood × length	0.01	0.13
Group (CA compared to DYS)	1.75***	0.33
Group (CA compared to RA)	1.12**	0.35
Group (CA vs DYS) × frequency	0.58	0.44
Group (CA vs RA) × frequency	0.81~	0.46
Group (CA vs DYS) × neighbourhood	−0.22	0.19
Group (CA vs RA) × neighbourhood	−0.26	0.22
Group (CA vs DYS) × length	0.14	0.18
Group (CA vs RA) × length	0.08	0.20
Random effects (variance components)		
Item (intercept)	0.51	
Participant (intercept)	0.59	
Fit statistics		
−2LL	−1,233	
AIC	2,500	
BIC	2,618	

**p*=<0.05

***p*=<0.01

****p*=<0.001

~ 0.05<*p*<0.10

"cáfe" → /café/ (see Table 5). The first two categories are self-explanatory and the last consisted of errors in which all phonemes are produced correctly, but the word was stressed on the wrong syllable. It can be seen that the RA children made more errors of all kinds than the CA children and that the dyslexic children made more errors than the RA children. Subject group was significantly associated with variation in the frequency of word errors (χ^2 (2, N=110)=31.4, p<.001) and of nonword errors (χ^2 (2, N=180)=54.9, p<.001) but not of stress errors (χ^2 (2, N=43)=1.7, p=.42).

Table 5 Summary of frequencies of different error types produced by each participant each group

Total number of errors=333			
Error type	Group		
	Chronological-age-matched	Dyslexic	Reading-ability-matched
Word substitutions	16	63	31
Nonword errors	24	104	52
Stress errors	11	18	14

Most errors were formally related to target words, where a formal relation, in an orthographically transparent language, may be considered to be a phonological or an orthographic relation. Errors tended to differ by the deletion (e.g. "juicio" → /juico/), addition (e.g. "lengua" → /lenguaje/) or substitution (e.g. "nave" → /nove/) of one or two graphemes. We computed the formal similarity of errors to targets using the MatchCalculator application (by kind permission of Dr. Colin Davis), calculating the relative proportion of graphemes shared by a target and an error in the same position such that, for example, "nostalgia" → /mostalgia/ scores 0.89, whereas "nostalgia" → /nostalagia/ scores 0.67. This method of scoring similarity assumes slot, or absolute, letter position coding, in common with most current models of word recognition (e.g. the dual route model, Coltheart et al., 2001) but not, for example, the SOLAR model (Davis & Bowers, 2006). The mean similarity of both word and nonword errors was greater than 0.5 (word errors, M=0.63, SD=0.27; nonword errors, M=0.64, SD=0.24).

Reading speed

Reading times per list are summarised in Table 3. A number of trends are evident. Firstly, younger (RA) and dyslexic children read more slowly than CA children. Secondly, more frequent shorter words with larger orthographic neighbourhoods elicit faster reading times. We tested these trends in an analysis of variance on the by-subjects reading times per list, with group as the between-subjects factor and frequency, neighbourhood and length as within-subjects factors.

We note that we checked for the presence of outlier times in our dataset by standardizing data and identifying which of the resulting z scores had absolute values greater than 2.58, a value equalled or exceeded by 1% of a normal distribution (Field, 2007). We found that eight data points could be identified as outliers in this fashion and conducted analyses both on a dataset with all data points and on a data-set with the outliers removed. Our analyses indicated that the significance or direction of effects did not differ between the two analyses, so in the following we will report the results of the analysis conducted on the data set without outliers removed.

We found that reading times were significantly affected by main effects of group ($F(2, 63)=8.86$, $p<.001$), frequency ($F(1, 63)=73.76$, $p<.001$), neighbourhood size ($F(1, 63)=17.53$, $p<0.001$) and length ($F(1, 63)=201.62$, $p<.001$). There were, in addition, a number of significant interactions: a significant interaction of group and length ($F(2, 63)=5.24$, $p=.008$), an interaction of frequency and length ($F(1, 63)=13.15$, $p=0.001$), a significant interaction of neighbourhood size and length ($F(1, 63)=12.14$, $p=0.001$) and a significant interaction of frequency, neighbourhood and length ($F(1, 63)=11.45$, $p=0.001$). No other effects were significant at the 0.05 criterion level.

On average, the RA children's reading times were longer (estimated marginal mean (EMM)=18.29, SE=1.2) than those of the CA children (EMM=14.75, SE=1.2), and the dyslexic children's times were longer still (EMM=21.92, SE=1.2). However, a priori multiple comparisons (Bonferroni corrected t) indicated that, whereas the dyslexic children's times were significantly longer than those of the CA children ($p<.001$), the RA children's times did not differ from the dyslexic nor from the CA group's times.

Simple effects analyses indicated that the effect of length was significant for each group when considered separately (simple effects: $F_{CA}(1, 21)=98.69$, $p<.001$; $F_{DYS}(1, 21)=51.71$, $p<0.001$; $F_{RA}(1, 21)=135.11$, $p<0.001$). Furthermore, simple effects analyses indicated that the effect of length was significant under each frequency condition ($F_{low}(1, 63)=153.99$, $p<0.001$; $F_{high}(1, 63)=171.05$, $p<0.001$) as well as under each neighbourhood condition

($F_{few}(1, 63)=129.32, p<0.001$; $F_{many}(1, 63)=194.96, p<0.001$). We note that the size of the length effect appears to be smaller for dyslexics (r=0.84) than for CA children (r=0.91) or RA children (r=0.93), although the effect is clearly massive in all groups; this is a little surprising considering the differences to be seen in Table 3 but is no doubt because of the greater error variance associated with dyslexic responses. The size of the length effect is similar under each neighbourhood and frequency condition, although a trend is evident, whereby, the length effect is a little greater under the many neighbours (r=0.87) compared to the few neighbours (r=0.82) condition and under the high frequency (r=0.86) compared to the low frequency (r=0.84) condition.

Results summary

The level of reading accuracy overall was high across experimental conditions. The older CA-matched control group made very few errors, although the few errors that they did make were more likely to be made to low frequency words. The younger RA-matched control group made more errors, and the dyslexic group made the most number of errors. These groups, also, evidenced a tendency to be influenced by the frequency of words. No other effects were apparent. Most errors consisted of word substitutions or nonword errors. As would be expected, the dyslexic and RA groups tended to make more of each kind of error than the CA group. Both kinds of errors exhibited a high degree of formal similarity to target words. A small number of stress errors were observed.

We found a significant effect because of group, as dyslexic children were slower than CA children. However, importantly, the dyslexic children's reading times did not differ significantly from the RA group's times overall. We found that all other main effects were significant: frequency (reading times to low-frequency words were longer), neighbourhood size (times to words with fewer neighbours were longer) and length (times to longer words were longer). We also found a number of significant interaction effects. Of particular interest was our finding that the effect of length was significantly modulated by influences due to reading ability (group × length interaction), frequency (frequency × length) and neighbourhood (neighbourhood × length).

Discussion

It is striking that the accuracy of all children was relatively high, even those dyslexic children whom standardised testing had indicated bore quite severe reading difficulties. This high level of accuracy was expected, however, given the regularity of orthography-to-phonology mappings in Spanish. In this respect, our findings are consistent with those yielded by investigations of developmental reading in other languages with transparent orthographies.

The dyslexic and ability control group children in our study did make significantly more errors than the older age-matched control group, and the errors that were made consisted of word or nonword substitutions of high phonological similarity to targets. Importantly, the data indicate that while the dyslexic and controls may have differed in the quantity of errors produced, they did not differ in the kinds of errors that were made. This pattern seems to be best explained by an account in which the processes that support the production of word phonology operate at a lower level of effectiveness but are not qualitatively different in Spanish-speaking children with reading difficulties compared to children of age-average ability.

That the errors often occurred in the form of additions, deletions or substitutions suggests problems in phonological transcoding of print consistent with a general phonological deficit but also with possible difficulties at the levels of orthographic processing, orthography-to-phonology mapping or, specifically, the assembly of phonological output. One might expect that a difficulty in the completion of orthography-to-phonology mappings would lead to errors composed mostly of single phoneme substitutions where substitutions are phonetically similar to target phonemes. In comparison, a difficulty specific to orthographic processing would be expected to give rise to substitution, addition and deletion errors, as well as to stress errors. Further experimental work (Davies, Glez & Cuetos, in preparation) is being undertaken to elucidate the deficits that underlie error production in our reader sample; however, the present data alone suggest the consequences of developmental problems including but not confined to a phonological deficit.

We found that the dyslexic and ability-matched controls were slower in reading than were the age-matched controls; however, the dyslexic group was not significantly different from the ability-matched control group in reading times. If one can assume a higher level of general cognitive skills in older dyslexic children compared to younger ability-matched controls, then the data suggest that a higher level of general cognitive ability might be sufficient to compensate for phonological coding problems in maintaining the speed of reading. As our data consist of list reading times, it may be that greater intellectual maturity affords the computational resources necessary to adjust response output to narrow the interval between responses, shorten response durations, or both, to meet the demands for speeded responding. However, the intelligence quotient numbers tended to be higher for the ability-matched compared to the dyslexic groups, indicating that, at minimum, the abilities tapped by the BADYG, the intelligence test battery we employed, do not also tap the abilities that would support the effort to shorten reading times.

Our observations of the main effects of frequency and length on reading times and of frequency on accuracy serve to replicate previous findings in Spanish and in other languages with transparent orthographies. We also contribute an extension to current data by observing an effect of orthographic neighbourhood size on reading times. The effect of length can be characterised as arising from a number of possible sources, warranting further investigation. Longer words may elicit longer reading times because they require more eye gaze fixations for adequate uptake of letter identity and position information. A length time cost can also be linked to the letter-by-letter cost of sublexical phonological coding or to the related cost of the assembly of the outputs of such coding. The frequency and neighbourhood size effects can be explained in the terms both of localist and of connectionist models of reading: in general, as the facilitation of reading processes as a result of the effects of the experience of words. Following the analysis put forward by Seidenberg & McClelland (1989), we can say that the frequency and neighbourhood effects reflect the experience of the target word itself and of its neighbours. In the case of the frequency effect, the influence on reading accuracy and times arises from the effect of the greater experience accumulated of higher frequency target words, whether that effect is exerted through variation in the degree of activation spreading from orthographic to phonological representations (the dual route model, Coltheart et al., 2001) or through variation in connection weight strengths (connectionist models, e.g. Seidenberg & McClelland, 1989). The neighbourhood size effect can be construed as the facilitation of target word processing by the effect of previous experience of orthographic neighbours, whether such facilitation should be framed in terms of lexical activation, feeding back to letter (Andrews, 1989) or to phoneme (Coltheart et al., 2001) representations.

Significantly, the neighbourhood effect was found to modulate the length effect. The numeric difference between reading times to long compared to short words is greater when long words also have fewer neighbours. This trend suggests that lexical experience (construed broadly) serves to militate against the costs of an analytic or sub-lexical, phonological coding strategy. The observation of this interaction contrasts with Ziegler et al.'s (2003) finding that the effects of length and body neighbourhood size interacted for English but not for German children. The variation in the size of the length effect may have various causes. Orthographic coding may be facilitated through the activation of letter representations via feedback after activation by a target letter string of neighbours' orthographic representations, or it may be the case that larger grain-size visual attention windows are afforded (Ans et al., 1998; Plaut, 1999) by the recognition of the target word, a recognition that is facilitated by knowledge of orthographic neighbours. Moreover, output preparation of a target could be primed, as a number of lexical phonological representations, the target's neighbours, are activated by the same letter string. Thus, at both input and output, the effect of having more orthographic neighbours would tend to diminish the cost of greater word length. It is difficult to view the neighbourhood size effects without concluding that lexical experience counts, no matter what nature of representations are assumed. We submit that the neighbourhood size effect can be taken to show how children learning to read in transparent orthographies do not rely solely on sublexical knowledge in reading.

The length by frequency interaction runs counter to the majority of observations of these effects. We have no strong biases concerning the explanation for this reversal. For short words, there is some advantage to be gained by experience, by higher frequency or by larger neighbourhood size, but this advantage is constricted by a ceiling effect on performance such that reading times cannot be pushed to be faster beyond a certain point. If one considers the reading speed averages presented in Table 3, however, it is apparent that the difference between reading speed to long and to short words is largest where the words are high frequency but have fewer neighbours. This suggests a decisive role for orthographic neighbourhood size that manifests itself as the frequency by length interaction observed. It could be that neighbourhood size is more important for words of higher frequency, because it is for those higher frequency words that more firmly established lexical representations exist and, thus, for those words, that some benefit may be gained by greater experience with a consequence seen in a greater length effect. Further investigation will be required to track the length effect over a broader section of the development trajectory to test this account.

Of central concern in our investigation was the character of reading development in Spanish. The numeric difference in reading speed to long and short words was greater for the dyslexic and ability-matched children compared to the age-matched children. The size of the length effect, computed as r, was smaller for the dyslexic children compared to the control group children, smaller for the age-matched controls compared to the ability controls. There are two things evident in the data. The first is that, as performance improves with age and ability, so also variance in that performance shrinks. An effect size measure computed in terms of the F ratio will be larger where variance is smaller. This is an effect similar to a television picture becoming clearer as visual noise is decreased. The second thing that is evident in the data is that the observed difference because of word length on reading times does decrease with age and reading ability. We suggest that happens because, as development progresses, a number of changes occur within the reading system while it approaches maximum efficiency. Among these, one can expect that grapheme–phoneme correspondences will be executed more efficiently and that lexical orthographic representations will become established or strengthened; in this view, one presumes the existence of lexical phonological representations. Both changes would tend to diminish the size of a length cost for reading performance. Alternatively, in the terms of a connectionist account of the reading system, increasing experience will support the establishment of broader visual attentional windows, permitting more of a letter string to be processed at each fixation (Plaut, 1999). If phonological output is specified in parallel, such widening of the visual attentional window would diminish the length effect.

Limitations

Further experimental work, now in progress and being planned, would address a number of limitations of our study.

We believe that the use of reading lists as an experimental method is an important means of addressing experimental questions to large samples of participants. Moreover, we believe that reading times recorded with the list technique constitute a measure that combines accuracy with fluency and that this is particularly appropriate for the study of reading in a transparent orthography, as we indicate in the "Introduction". However, we acknowledge that the use of computerised, discrete trial, test methods would support more fine-grained statistical analysis and are, in fact, conducting experiments with just such techniques.

Secondly, we acknowledge that the reading process is about more than just the mapping between spelling and sound. Thus, ongoing in our laboratory is a study in which we investigate how access to the lexicon and, thence, to meaning develops over time in children. We believe that of particular interest is the possibility that children more readily activate representations at the semantic level from partial orthographic information as their developmental requirements shift from getting the sound of the word correctly to getting the meaning in a timely fashion. Our study will encompass experiments probing both single-word recognition and the recognition of words within connected text.

Conclusions

Our results consistently show how lexical knowledge influences the reading process. This is the case even in children reading at the same level as that typical of 9 year olds in the third year of primary school in Spain, as were our dyslexic group and ability-matched control group children on average. This is manifest in the effects caused by frequency and neighbourhood size. Our data do not speak to the ongoing debate concerning the most appropriate way to model reading, whether one must assume localist or distributed representations, as either approach can be taken to account for our findings. We argue, however, that the important conclusions to be drawn are that dyslexic children resemble the ability-matched controls, that dyslexic children can, to some extent, compensate for reading time disadvantages and that a lexical influence can be seen in the reading of all groups, even the youngest and least able.

Future research must be aimed at considering in further detail the mechanisms by which increasing reading experience can support increasingly effective reading performance. This will depend upon the use of sensitive measures of reading experience. In combination with such measures, fruitful investigations will likely probe the importance of phonological processing skill but also of orthographic processing skill. In particular, it seems to us likely that increasing experience will be found to be associated with a growth in the size of the units (e.g. spelling units) important to the spelling–sound mappings that underly word naming or access to meaning from word recognition.

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